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Ultrasonic attenuation in single crystal nickel at 298 and 80°K.

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Experimental values of second and third order elastic constants have been used in computing the values of non-linearity constant D which are instrumental in conversion of acoustic wave phonons to thermal phonons. The attenuation suffered by longitudinal ultrasonic waves propagation along $< 100 >$ and $< 110 >$ directions and shear waves polarized along $< 100 >$ and $< 110 >$ directions, owing to phonon viscosity and thermoelastic phenomenon have been determined by using the above D values at 298° and 80°K. Phonon viscosities and dislocation drag coefficients are also calculated and the results obtained are in good agreement with the previous predictions.

1. Introduction

Extensive acoustic attenuation measurements made by different workers (Mason *et al* 1964, Mason 1965, Mason *et al* 1966, Mason 1967, Hanson 1967, Lewis 1968) have shown that the major part of ultrasonic attenuation in solids occurs because of the interaction of thermal phonons with ultrasonic waves, i.e., the phenomenon of phonon viscosity which provides a good probe (Mason 1960) for the study of dislocation in solids. This type of interaction is possible only if $\omega\tau th \ll 1$, where τth is the thermal phonon relaxation time and ω is the angular frequency of the acoustic wave (Mason 1965). Because of its very small relaxation time, individual phonon becomes insignificant and the idea of phonon gas having microscopic parameters is described. When sound waves propagate through the phonon gas, its microscopic parameters are varied periodically and the equilibrium is displaced. To restore the equilibrium, irreversible processes occur which cause attenuation losses. In these losses, Akhieser (1939) and thermoelastic losses are the important one. Akhieser loss is caused by the relaxation of thermal energy between different phonon branches heated to different extents by ultrasonic waves and the latter by the thermal conduction between the compressed and expanded parts of the acoustic wave. This type of loss contributes nothing to the total attenuation in shear wave propagation because the volume for it, remains intact and the heating effects become zero.

From the analysis of phonon conductivity, Singh & Verma (1968) showed that the non-linearity constant D is temperature dependent. Here, we also

have evaluated the values of constant D at 80° and 298° K from second and third order elastic constant data in different directions of propagation of longitudinal and shear waves that provides partial support to above fact. Ultrasonic attenuation losses and dislocation drag coefficients have also been computed for the above said temperatures.

2. Theory

The Akhieser loss (1939) caused by the phonon viscosity may be expressed in mathematical form as,

$$\alpha \quad \frac{E_0(1/3D)}{2\rho V^3} \quad \frac{\omega^2\tau}{1+\omega^2\tau^2}$$

where the product $\omega\tau \ll 1$ is a necessary condition for the interaction at the said temperatures to be possible and the above expression for longitudinal wave propagation may be written as,

$$\alpha(np/cm) \quad \frac{E_0(1/3D)_l}{2\rho V_l^3} \omega^2\tau_l \qquad \ldots (1)$$

Here, E_0 is the thermal energy density, ω the angular frequency of the acoustic wave, ρ the density and V_l is the velocity of longitudinal acoustic wave. In the above equation, ρ is given in gm/c.c, D_l is a dimensionless constant and rest other terms have the same units as given in table 1. A similar relation holds good for shear waves. The relaxation times τ_1 and τ_s are related with each other by the following expression (Mason 1965),

$$\frac{1}{2}\tau_1 = \tau_s = \tau_{th} \quad \frac{3K}{C_v V^2} \qquad \ldots (2)$$

where K is the thermal conductivity, τth is the thermal relaxation time for the exchange of thermal energies, C_v is the volume specific heat and V is Debye average velocity. The non-linearity constant D used in eq (1) is obtained from the following relation,

$$D = 9 < (\gamma_l^j)^2 > -3 < (\gamma_l^j)^2 > \quad \frac{\rho C_v T}{E_0} \qquad \ldots (3)$$

where T is the absolute temperature and (γ_l^j) are the Grueisen numbers, corresponding to a particular direction of propagation and polarization. The thermoelastic attenuation is computed from,

$$\alpha(np/cm) = \frac{\omega^2 < \gamma_l^j >^2 KT}{2\rho V_l^5} \qquad \ldots (4)$$

The phonon viscosities for longitudinal and shear waves are,

$$\eta_l = 2D_l\left(\frac{E_0K}{C_pV^2}\right); \quad \eta_s = D_s\left(\frac{E_0K}{C_pV^2}\right) \qquad \ldots (5)$$

which are related with drag coefficients as follows (Mason *et al* 1966a)

$$B_{screw} = 0{\cdot}071\eta \qquad \ldots (6)$$

and

$$B_{edge} = \frac{0{\cdot}0532}{(1-\sigma)^2} + \frac{0{\cdot}0079}{(1-\sigma)^2}\left(\frac{\mu}{K}\right)^2\chi \qquad \ldots (7)$$

where σ is the poisson's ratio and

$$\mu = C_{44}, \quad K = C_{11} + 4/3C_{44}$$

$$\chi = \eta_l - 4/3\eta_s.$$

3. Results and Discussion

Primary physical constants required for the detailed calculations are shown in table 1 for the ferromagnetic crystal Ni at 80° and 298° K. The values of specific heat, C_p, and thermal energy density, E_0, at said temperatures have been extracted from the literature (AIP, 1957) as a function of θ/T. Thermal relaxation time has been calculated from eq (2), using the lattice conductivity (K_p) values. Since in metals, electron and phonon both carry the thermal energy but in equilibrium only phonon takes part, it was necessary to separate the phonon conductivity from electronic conductivity. Here, in nickel, this has been done by a theoretical formula of Liebfried and Schlomann (1954) as given below.

$$K_p(W/cm\ \ K) = \frac{3{\cdot}6aA\theta^3}{\gamma^2T}$$

Table 1 Primary physical constants for Ni at 298° and 80°K.

Temperature °K	V_l (m/sec)	V (m/sec)	C_p (10^7 erg/cm^3)	E_0 (10^9 erg/cm^3)	τ_{th} (10^{-11} sec.)
298	5302	3708	3·345	6·158	0·3215
80	5442	3800	0·1284	0·9198	2·212

where a is the lattice constant, A is a constant equal to 92·9 for metals, subscript p represents phonons, and γ is the volume Gruneisen constant (Mason *et al* 1966). Above formula approximates K_p values which overestimate by a factor of 3/2 from the measured values.

Second and third order elastic constants, determined experimentally by Sharma & Reddy (1973a, 1973b) are used in computing the values of average Grueneisen constant $\langle(\gamma_i^j)\rangle$, average square Grueneisen constant $\langle(\gamma_i^j)^2\rangle$ and acoustic coupling constant D from Mason's (1964, 1967) theoretical formulae for cubic crystals. The $\langle(\gamma_i^j)\rangle$ and $\langle(\gamma_i^j)^2\rangle$ for longitudinal waves and $\langle(\gamma_i^j)^2\rangle$ for shear waves have been evaluated by averaging over 39 pure modes ($\langle(\gamma_i^3)\rangle = 0$) and the results obtained are presented in table 2

Table 2. Grueneisen numbers and non-linearity constant D for Nickel.

Direction	Temp. °K	$\langle(\gamma_i^j)$ Long	$\langle(\gamma_i^j)^2\rangle$ Long.	Shear	Long	Shear
100	298	1·512	4·565	0·115	29·985	3·735
	80	2·213	6·688	0·311	11·552	3·096
110*	298	1·639	3·769	4·523	20·881	10·707
	80	1·901	4·695	4·080	6·365	36·720

* For shear wave polarization is along 110 direction

From table 2, it is clear that the D values provides striking support to the fact that the constant D is temperature dependent (Singh & Verma 1968) Further, on experimental basis, the above fact was tested by Tripathi *et al* (1972) for only longitudinal wave propagation along $\langle 110\rangle$ direction in the case of Cu and was found valid Here, we have also tested it to shear waves polarized along $\langle 100\rangle$ and $\langle 110\rangle$ directions in single crystal Ni which again retains its validity there. As similar to other cubic crystals studied by Kor *et al* (1972, 1973, 1974), the non linearity constant D for the longitudinal wave is found to be greater from 5 to 17 times than that for shear wave along $\langle 100\rangle$ direction in nickel The value of D_l/D_s decreases rapidly with temperature. The most significant observation that can be made regarding the information of the table 2 is that the value of D for longitudinal wave changes more rapidly with temperature than the value of D for shear wave in both directions. Moreover, this behaviour of D values is justified (from eq. (1)) by the temperature dependance of ultrasonic attenuation in Ge and Si obtained experimentally in the sense that the ultrasonic attenuation (Mason 1965) for longitudinal wave also changes more rapidly than for the shear wave as the temperature decreases

Table 3, enlists the values of ultrasonic attenuation due to phonon viscosity and thermoelastic effect along the two directions $\langle 100\rangle$ and $\langle 110\rangle$ ($1\bar{1}0$ for shear wave) for different types of waves. Dislocation drage coefficients of both the types (Screw & Edge) are also presented in table 3. In the above calculations of drag coefficients, Burger's condition, $a = 3/4b$, where a is the dislocation core radius and b is Burger's vector, has already been assumed

A perusal of Table 3, shows that ultrasonic attenuation is dependent on temperature and the direction of propogation of acoustic wave. As similar to noble metals (Kor *et al* 1972), and cesium halides (Kor *et al* 1973), the (α/f^2) values along the two directions are unequal in present case also. So for as the question of temperature dependence of (α/f^2) along $<100>$ direction is concerned, it falls of more rapidly for longitudinal waves than the shear waves as the temperature decreases and provides a theoretical support for the experimental studies (Mason 1965) of the ultrasonic attenuation in Ge and Si. Moreover, a similar trend has been observed experimentally by Basu (1974) in single crystal Ni for the variation of ultrasonic attenuation with temperature and direction for longitudinal waves. Their studies consist of magnetic contribution to ultrasonic attenuation also. The magnetic contribution, in our case, has been eliminated by keeping the crystal sample in transverse saturation magnetic field (Sharma *et al* 1973a, 1973b). Moreover, our results should be experimentally true because we have considered thermal conductivity due to phonon only instead of total thermal conductivity. The total thermal conductivity causes the result several times higher than the experimental values for conducting crystals (Kor *et al* 1972) and semi-conductors (Kor *et al* 1973a). Still better results are expected from the exact knowledge of K_p (Phonon conductivity) values. It is interesting to note (See table 3) that the Akhieser loss (1939) is dominant over the thermoelastic loss which again supports the conclusions drawn experimentally by different workers (Mason *et al* 1964, Mason 1965, Mason *et al* 1966, Mason 1967, Lewis 1968).

Table 3. Attenuation of longitudinal and shear, acoustic waves and drag coefficients for screw and edge dislocations along the $<100>$ and $<110>$ directions at 298° and 80°K for nickel. (A represents Akhieser and *T* represents thermoelastic).

Direction	Temp. °K	(p/f^2) *A* (10^{-16} *dB* sec²/cm)		$(\alpha/f^2)_T$ (10^{-17} *dB*) sec²/cm	*B* (Poise)		*B* (Poise)	
		Long.	Shear		Long	Shear	Long.	Shear
100	298	0·511	0·093	0·184	0·249	0·010	0·220	0·012
	80	0·186	0·073	0·237	0·536	0·072	0·470	0·081
110*	298	0·356	2·257	0·213	0·174	0·170	–	
	80	0·102	0·868	0·175	0·295	0·852	–	–

* For shear wave polarization is along $<1\bar{1}0>$ direction.

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